Sensitivity Analysis of the Galileo Integrity Performance Dependent on the Ground Sensor Station Network

Helmut Blomenhofer, Walter Ehret, Hua Su, *THALES ATM GmbH*

Eduarda Blomenhofer, *NavPos Systems GmbH*

BIOGRAPHY

Dr. Helmut Blomenhofer

After finishing University he was Research Associate at the Institute of Geodesy and Navigation (IfEN) of the University FAF Munich from 1990 to 1995 and did research and software development in high-precision kinematic Differential-GPS.

From March 1995 to December 1997 he was at Daimler-Chrysler Aerospace AG (Dasa); NFS Navigations- und Flugführungs-Systeme being responsible for the development of an Integrated Navigation and Landing System (INLS) for aircraft precision approaches and automatic landings. From January 1998 to 2001 he was the EGNOS Programme Manager at the EADS subsidiary Astrium GmbH located at Friedrichshafen.

Since 2002 he is GNSS Business Development Director at Thales ATM, Germany.

Dr. Hua Su

is the GNSS Systems Engineer at Thales ATM, Germany. He holds BSc and MSc from a Chinese technical university and Dr. –Ing. from the University FAF Munich, Germany. He has worked on GPS involving precise orbit determination, differential GPS, satellite navigation and GPS receiver software development for more than 20 years. From 1996 to 2000, he worked as Research Associate at the Institute of Geodesy and Navigation (IfEN) of the University FAF Munich for EGNOS and Galileo projects. After joining Thales ATM, he has been involved in EGNOS System AIV project (Assemble, Integration and Validation) charging EGNOS system performance analysis and tests for 4 years. From May 2005 he works for Galileo projects regarding Galileo integrity analysis and offline data processing.

Walter Ehret

graduated as an Aeronautical and Space Engineer from the Technical University (TU) of Braunschweig, Germany in 1996. Since 1996 he is involved in research and engineering activities related with Satellite Navigation. He is currently working as Systems Engineer at THALES ATM in Langen where he is involved in Galileo related tasks and particularly Integrity related issues.

Eduarda Blomenhofer

is Managing Director of NavPos Systems GmbH, a German SME which specialised in the satellite navigation related systems engineering, software development and consultancy. She owns an Engineer Degree in Surveying/Geodesy from the Porto University, Portugal. She is working in satellite navigation since 1990, with activities on high precision differential GPS algorithms and software for real time applications, data processing and service volume simulation for GPS, Glonass, GBAS, SBAS and Galileo.

ABSTRACT

The European Satellite Navigation System Galileo which is currently under development offers a number of services. The Galileo Safety Of Life (SOL) service is intended for use with safety critical applications, particularly in the transportation sector. The SOL service provides standard PVT (Position Velocity Time) to the users combined with an integrity information service. This service will be provided on a global scale.

The SOL service will broadcast safety related information in form of several parameters. One of these parameters is the SISA - the Signal In Space (SIS) Accuracy, which is broadcast and assigned to each Ephemeris broadcast. SISA shall be a bound for the true SIS Errors with definite probability and is determined in the Galileo Control Center which determines the Orbit&Clock parameters. The SISA in itself as a predicted parameter (for up to 100 minutes) will be validated in real time using observations of a global network of Monitoring Sites. These Galileo Sensor Stations (GSS) are a fundamental part of the Galileo Ground Segment. In the final deployed System the number of GSS is in the order of thirty to forty units. The GSS Network Geometry will influence the observability of the SISE, the

so called SISMA (SIS Monitoring Accuracy) parameter, which is also broadcast regularly within the SOL data frames. Finally with the determination of SISE the SISA can be evaluated and broadcast using the Integrity Flags which are determined by the Integrity Determination Process in the Galileo Ground Mission Segment.

This paper describes the work and preliminary results to analyse the sensitivity of the Galileo SOL performance to the GSS network. The new proposed Galileo Integrity concept which was published by ESA/GaIn was implemented in an advanced Service Volume Simulator. Depth of Coverage for the Galileo satellites and SISMA coverage are calculated for assumed variations of the number and distribution of the GSS global network. Finally the Integrity Risks are calculated on a global scale and for different time frames. Special attention is drawn to the required Availability figures as referenced in Galileo System requirements for SOL services (different levels) and mapped to the Aviation standards as published by ICAO SARPS for GNSS Radio-Navigation services.

The present work will outline the performance of the Galileo Integrity determination and the sensitivity to Sensor Station outages. The results will demonstrate how the performances of Galileo SOL service can vary with place and time, compared with the guaranteed or specified performances.

INTRODUCTION

Galileo will offer its users four basic services based on SIS-only: the Open Service, the Safety-Of-Life Service, the Public Regulated Service and the Commercial Service. Additionally there will be a Search And Rescue Service provided.

This paper will concentrate on aspects of the Safety Of Life (SOL) service, which is intended for Safety Critical user operations, with a clear guarantee and liability scheme. The user groups for safety critical applications are mostly found in the different modes of transportation which are Road, Rail, Marine and Air. Each of them generates requirements or standards and there exist various definitions. For the analysis presented in this paper, the Galileo requirements are used and compared with the ICAO aviation requirements as found in the Standards And Recommended Practices (SARPs).

The safety critical application of satellite based 'Global Navigation and Landing' systems in civil aviation in principle allows navigation and guidance of aircraft throughout all phases of flight and weather conditions. The advantages of satellite based navigation systems are obvious. However for safety critical applications, today's safety level of navigation and landing systems at least has to be maintained, and if possible, it has to be improved.

The embedded Integrity function in the Safety of Life Service of the Galileo System is the key for the ability to serve as navigation means in safety critical applications. It represents the major difference compared to the existing US NAVSTAR GPS.

This Integrity service is characterised by the provision of what is commonly called a Ground Integrity Channel (GIC), which is in the Galileo case an integral part of the whole System and not an add-on as e.g. WAAS for GPS. One of its essential attributes is the distribution of the Galileo Sensor Station (GSS) network and the quality of the observable made. Before coming to the specifics of the Galileo Integrity Concept first the requirements for the resulting service level shall be discussed.

AVIATION REQUIREMENTS ANALYSIS

ICAO Annex 10 (SARPS Radionavigation Aids) defines the requirements for the different phases of flight [1]. Figure 1 compares the Required Navigation Performance (RNP) per phase of flight with the existing or expected GNSS system performance.

The use of GPS together with RAIM fulfills requirements down to the Non-Precision flight phases.

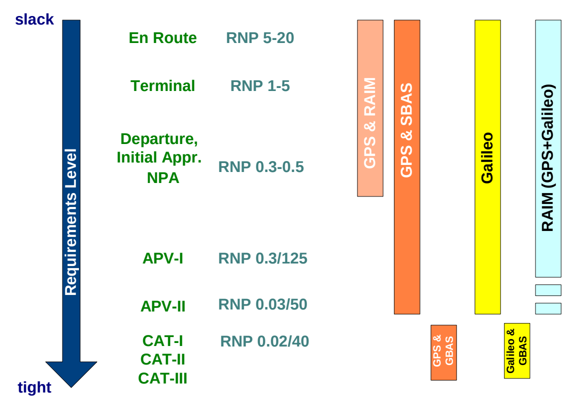

Figure 1: Aviation Phases of Flight versus GNSS Performance

The introduction of Satellite Based Augmentation Systems (SBAS) like WAAS in US, MSAS in Japan and EGNOS in Europe improves the capability of GPS in terms of accuracy but especially in terms of System Integrity such that GPS/SBAS devices can fulfill at least APV-II requirements. A comparable level of performance is intended for Galileo. The following tables list the ICAO and Galileo Mission requirements.

Table 1 shows the Galileo requirements for the Galileo Safety Of Life Service as stated in the Mission Requirements Document [2]. Table 2 lists the requirements found in ICAO Annex 10 for GNSS [1]. The comparison of Table 1 and Table 2 yields that the Galileo System aims to be used as a certified navigation means for the flight phases Remote/Oceanic En Route down to non precision approach plus the new defined approach categories with vertical guidance APV-I and APV-II without the need for local or regional augmentation.

Accuracy (95%)	horizontal: 4m
	vertical: 8m
Availability	99.8 % of service life time
Continuity Risk	< $8x10^{-6}$ / 15s
Integrity	HAL: 40m
	VAL: 20m
	TTA: 6 seconds
	Integrity Risk: < $2.0x10^{-7}$ / 150s (system contribution)

Table 1: Galileo Performance Requirements for the Safety of Life Service Level A

Accuracy (95%)	horizontal: 16 m
	vertical: 8 m
Availability	99.0% to 99.999%
Continuity Risk	< 8x10-6 / 15s
Integrity	HAL: 40m
	VAL: 20m
	TTA: 6 seconds
	Integrity Risk: < 2x10-7 / approach (SIS contribution)

Table 2: ICAO APV-II Requirements

For the following simulations and representation of results the following values are of special importance:

Alarm Limit: 20 m (vertical)

Availability: 99.8% (MRD requirement)
99.5% (SRD requirement)
99.0% (min. ICAO requirement)

GALILEO INTEGRITY CONCEPT

The Galileo SOL service will incorporate the provision of integrity information in its message structure. For the user Integrity Risk computation the Galileo System will provide the Signal In Space (SIS) quality in terms of three parameters called SIS Accuracy (SISA), SIS Monitoring Accuracy (SISMA) and Integrity Flags (IF).

The SISA shall bound the true SIS Errors (SISE) with a certain confidence to be allocated by the performance allocation process. Where SISE is a residual error composed of Satellite Orbit Parameter (Ephemeris) errors and Satellite Clock errors (after application of the Clock corrections). Physically the SISA will have the dimension meters and be a statistical parameter - a standard deviation. The SISA will be an outcome of the OD&TS process at System level and is as the Ephemeris and Clock correction parameters a prediction. These predictions are determined in a batch process updating the parameters each 10 minutes. However an uplink of the most actual set of parameters including SISA for broadcasting may take up to 100 minutes. Studies as [8] and GSTB-V1 experimentation [17] seem to show that this maximum update interval is sufficient regarding the Galileo Mission Requirements.

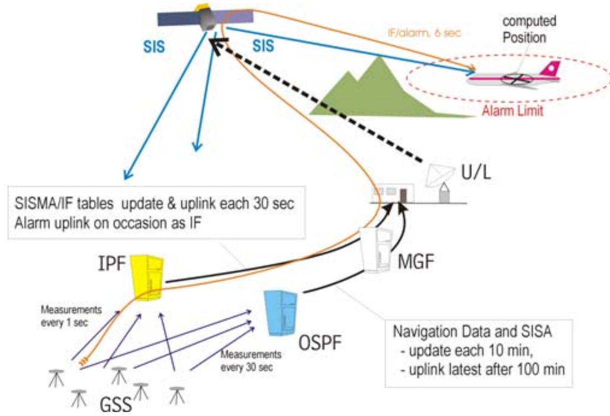

Figure 2: SISA/SISMA/IF signal loops

Since SISA is a prediction of the orbit and clock errors at least 100 min in advance, the dependence of it is strongly connected to the modeling quality. The SISA is expected to bound the errors under so called "nominal conditions" that means that all on board of the satellites and on ground segment will work in the specified frame for at least the next 100 minutes. This means also that the distribution of the true SISE will be zero centered Gaussian with the standard deviation SISA.

In case of a system failure, the user has to be alerted within a 6 seconds Time To Alert (TTA). Therefore an independent check of the SISA versus the SISE is foreseen in the Galileo Integrity concept each second. The indicator is the Integrity Flag (IF) which warns the user of the alert condition. Additionally the IF can be flagged preventatively whenever the system operator detects anomalies in the ground segment or the space vehicle. The additional parameter introduced - SISMA describes the SISE determination quality based on the GSS observation geometry of a satellite. SISMA will be updated in a shorter time interval of 30 seconds nominally. SISMA can also represent the status IF=true (don't use). In case of an alarm an update of the SISMA/IF tables is sent between the nominal update interval.

The general overview over the message flow is given in Figure 2. Without description of the total Galileo architecture the most relevant facilities for integrity determination are presented in brief.

The Galileo Sensor Stations (GSS) are distributed globally to cover the worldwide service performance requirements. The total number and site locations are still in discussion, since the constraining factors are not fixed yet.

Each GSS is equipped with several Galileo Receivers which observable are fed into two different communication channels one leading to the Orbit Synchronisation Processing Facility (OSPF) and the other to the Integrity Processing Facility (IPF). So two independent chains are installed, the Navigation chain and the Integrity chain.

The OSPF and IPF are part of the Galileo Control Center (GCC). The OSPF receives in 30 second intervals observable from all the GSS and is such computing the navigation message content with the SISA incorporated.

The IPF receives each second a measurement set of each GSS and is estimating for each Galileo satellite its current SISE which is then compared with the latest transmitted SISA in the Navigation message.

Regarding the transmission strategy the following baseline has been chosen so far:

The Safety Of Life service incorporates the transmission on two frequencies, L1 and E5B.

SISA is updated at least with the Clock parameters in the Ephemeris message. The update rate is 100 minutes or shorter. Each satellite transmits SISA for itself only.

SISMA will be broadcast on at least 2 satellites per each possible user, containing SISMA values for several satellites in view. The update rate is nominally 30 seconds. If an alarm has to be raised, then a new SISMA table is broadcast as an alarm message. As in the SBAS case a certain value of the SISMA – Indicator will flag a "Don't Use" state or "Not Monitored" state. Alternatively a shorter alarm consisting of pure Integrity Flags can be sent with 1s-update. For SISMA representation four bits are foreseen (16 states), for IF two bits are foreseen (3+1 states).

This paper will however concentrate on the GSS network influence on the Integrity performance.

SISMA/SISE/IF ALGORITHMS

Though SISA is estimated by the OD&TS loop independently of the integrity determination processes, its representation and statistical characteristics play the basic role for provision of the overall Integrity. The SISA representation impacts directly on the SISE/IF computational algorithms and its statistical characteristics define a portion of integrity risk related with SISA, and hence, the sum of integrity risks associated with SISE/IF and P_{hmi} algorithms (P_{hmi} standing for Probability of Hazardously Misleading Information, or Integrity Risk). Several suggestions have been made for the SISA definition:

- An estimation of the bound of the SISE error with a certain confidence level [9].
- A prediction of the minimum standard deviation (1-sigma) of the unbiased Gaussian distribution, which over-bounds the SISE predictable distribution for all possible locations within the satellite coverage area [10].

SISE is the satellite-to-user error due to satellite navigation message clock and ephemeris errors, which is a function of time and user location [10].

The following SISA representations have been investigated:

a) Four dimensional vector SISE representation uses a vector $(\Delta\vec{R}_{eph}, \Delta clk)$ where $\Delta\vec{R}_{eph} = (\Delta x, \Delta y, \Delta z)$, Δclk are ephemeris and clock errors respectively. The ephemeris errors can be presented either in the ECEF frame or in the orbital frame. In case of ECEF frame the equivalent ranging error along the user-satellite line-of-sight (LOS), SISAu includes two terms. One is the projection of $\Delta\vec{R}_{eph}$ onto the user-satellite LOS and the other is the clock error Δclk .

b) Three dimensional vector SISE representation is described by a vector: $(\Delta AlongTrck,\ \Delta CrossTrck,\ \Delta Rad + \Delta clk)$ where $\Delta AlongTrck,\ \Delta CrossTrck,\ \Delta Rad$ are ephemeris errors $\Delta x, \Delta y, \Delta z$ expressed in the orbital frame.

In both cases finally a scalar representative for SISE is generated which is the projection of the SISE Vector to a line of sight to a SISEu reached at the Worst User Location (WUL).

To the authors knowledge the baseline algorithm will be a 3-parameter model, such that the simulations are based on this algorithm.

SISMA COMPUTATION

SISMA (or sigma-check) is a parameter, which shows at what accuracy level the Integrity Processing Facility (IPF) is capable to determine a satellite's SISE error comprised of ephemeris and clock errors. An IPF module was implemented in AVIGA to perform the simulations based on the Galileo Integrity concept.

The i-th satellite ephemeris and clock error in ECEF frame can be presented as

$$\Delta\vec{x}_i = (\Delta X_i \quad \Delta Y_i \quad \Delta Z_i \quad c\Delta T_i)^T$$

for four parameters estimation task (4P) and

$$\Delta\vec{x}_i = (\Delta X_i' \quad \Delta Y_i' \quad \Delta Z_i' \quad)^T$$

for three parameters estimation task (3P).

The three parameters task can be considered if instead of ephemeris error components there are taken their sums with projections of the clock error $c\Delta T_i$ onto ECEF axes.

The GSS measurement errors are introduced as by the noise vector $B = (b_1 \quad ... \quad b_j ... \quad b_n)^T$, where n is the number of GSS stations tracking i-th satellite and b_j is a Gaussian error with standard deviation

$$\sigma_j = \sqrt{SIG0^2 + SIG1^2 / \tan^2(El_{ji})}\ . \quad \text{(Eq. 1)}$$

$$Z = A \cdot X + B \quad \text{(Eq. 2)}$$

where

Z is the vector of residuals errors of GSSs;

A is a (n x 4) matrix of directional cosines between GSSs and satellite i;

$X = \Delta \vec{x}_i$

For the system of linear equations (Eq. 2), the weighted least square solution and its covariance error matrix can be found.

$$X_{est} = (A^T \cdot COV(B)^{-1} A)^{-1} A^T \cdot COV(B)^{-1} Z$$

(Eq. 3)

$$COV_{X_{est}} = (A^T \cdot COV(B)^{-1} A)^{-1} \quad \text{(Eq. 4)}$$

The solution X_{est} is just an ECEF vector of ephemeris and clock errors whereas an actual value of error experienced by the user is the projection of this vector onto the user – satellite Line-of-Sight (LOS), the vector

$a_{uS} = (e_{uX} \quad e_{uY} \quad e_{uZ} \quad 1)^T$. Then the estimation error for the user a_{uS} can be written as

$$\sigma^2_{SISE_{est}} = a^T_{uS} COV_{Xest} a_{uS} . \quad \text{(Eq. 5)}$$

The maximum value of $\sigma^2_{SISE_{est}}$ searched over the satellite footprint is called sigma-check or SISMA. The granularity of this search is specified by the Longitude/Latitude Worst User Location (WUL) Search Steps.

IF or SISMA Indicator is set to a four bit value which is formed as follows:

Set to 0 = “Not OK” if the required probability of false alarm Pfa is not satisfied.

If the satellite is monitored and the required probability of false alarm Pfa is satisfied then IF is the integer from 1 to 14 coding SISMA (σ_{CHECK}) obtained by the SISE algorithm.

IF = 15 means “Not monitored” status of the IF.

Thus, this approach provides the user with IF satisfying the required Pfa and broadcasting the coded value of SISMA. The latter should improve the integrity availability for different classes of users.

COMPUTATION PARAMETERS FOR SISMA

In the following the parameters which can be tuned in the Service Volume Simulator are listed. This are parameters for the GSS:

- Elevation Mask = 10 deg.

Error Budgets including:

A.)

- Receiver Noise
- Multipath residual errors
- Interference residual Noise
- Iono Residual Errors
- Troposphere residual errors

resulting in an elevation dependent GSS errors model according to (Eq. 1):

- *SIG0* = 15 cm
- *SIG1* = 12.5 cm

With these values the first batch of simulations has been performed in the following designated with **(A.)** or **model A.**

However it turned out that some other contributions to the GSS measurement quality might have not been taken into account by these values of parameters properly. Therefore an additional batch of simulation has been performed taking into account:

B.)

- GSS Clocks Synchronisation to GST (Galileo System Time) – 15 cm (0.5 ns)
- Antenna Position and Phase Center Error (+20%)

resulting in

- *SIG0* = 35 cm
- *SIG1* = 15 cm

The elevation dependent part (*SIG1*) has been raised by 20% to account for the lower allowed elevation mask (from 15 deg. down to 10 deg.) which could deviate from the model. The (Eq. 1) describes the degradation with elevation only down to 15 degrees well enough.

The other parameters taken into account have been derived from the recommendations by ESA [4], [10] and from [11].

For the orbit height above ground 23.222 km have been taken into account, according to a 29.600 km semi major axis.

DEPLOYMENT OF GSS STATIONS

Generally the following variables have to be considered for the network selection:

- Elevation Masks of the GSS
- required Depth Of Coverage (DOC, i.e. minimum number of GSS seen by each Galileo satellite)
- Measurement Quality at GSS level
- Performance of SISMA and SISE determination
- Redundancy Philosophy

The Galileo Sensor Stations (GSS) are distributed globally to cover the worldwide service performance requirements. Figure 3 represents the ESA recommended 30-GSS distribution for Service Volume Simulations in [4]. Additionally a 40-GSS network has been considered and analysed as discussions arise to extend the GSS network to 35 or even 40. The additional 10 GSS have been selected arbitrarily by the authors of this paper considering some gaps in the 30-GSS baseline network.

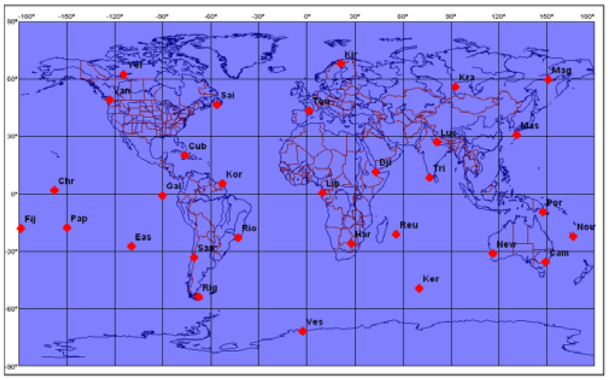

Figure 3: Global Deployment of a 30-GSS network

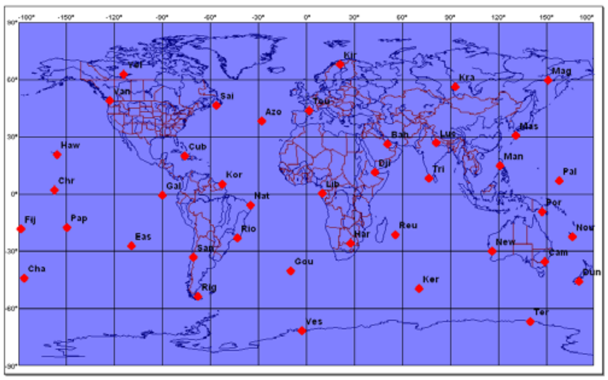

Figure 4: Global Deployment of a 40-GSS network

SIMULATION RESULTS : DOC & SISMA

As discussed above a 3-parameter SISE estimation model has been chosen. This would require at least 3 GSS to be visible from the satellite in any position along its orbit. This would mean to design a (Depth Of Coverage) DOC-3 network. Also a GMS (Galileo Ground Mission Segment) requirement is, that at least one additional GSS shall be visible from a satellite all the time. This would result in a DOC 4 network criteria. As a remark: for a 4-parameter model a DOC-5 would be needed.

There are many factors which will affect the Galileo SIS Performance. One of them is outage of GSS stations that can be temporarily caused by network (message gaps >2s), power supply failure and strong multi-path and strong interference etc.. Therefore such outage cannot be avoided and shall have an impact on the SISMA performance. The analysis has been done regarding four sceneries: outage of one, two, three and four GSS stations. In order to evaluate the influence caused by GSS station outage, the following two criteria are used in the analysis. First, according to the above said the Galileo IPF specification documentation [7] for SISMA computation with 3 parameter model, IPF needs at least 4 measurements from a Galileo satellite to compute nominal SISMA values. Second, SoL nominal maximum SISMA value shall not be larger than 70 cm. Therefore our analysis is to check whether any outage of GSS stations will cause these two requirement not to be met in some area.

As already mentioned the first check would be to analyse the DOC capability of a GSS network.

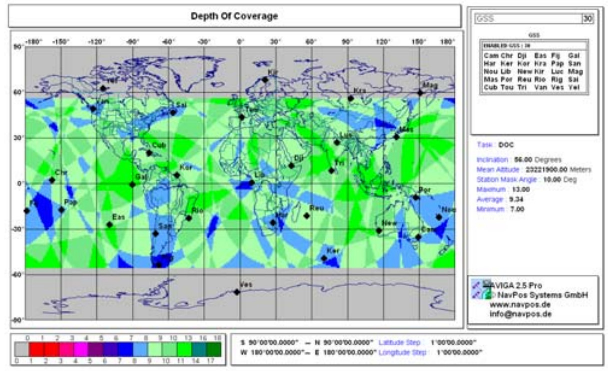

Figure 5: DOC coverage for a 30 GSS network

As can be seen, with the baseline GSS network the DOC is always above 7 and in average over 9. This is far above the required 4.

The next to prove attribute is the SISMA coverage based on this network. This is performed first for the GSS error modelling according to model **A.** mentioned above. The result is shown in Figure 6 showing that with this model SISMA is for all (projected) satellite positions smaller than the required 70 cm. It is in average as small as 23 centimeters and at most 48 centimeters in a region around New Zealand. To read this plot correctly, not New Zealand will have a problem (if any) but the whole region who "sees" a satellite right above New Zealand. This has to be reminded if regarding the User VPL computation results mentioned in the next chapters. This chapter will stay at analysing the SISMA performance related to the SISMA related requirements in [3].

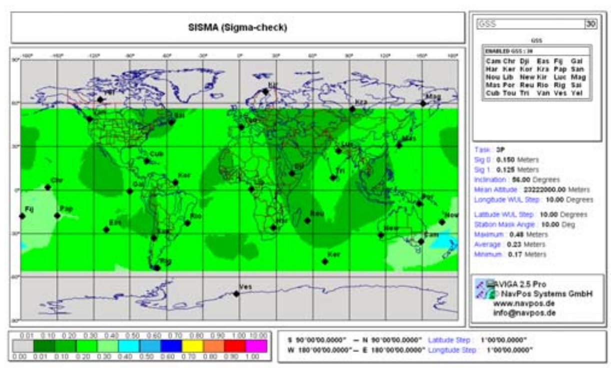

Figure 6: SISMA map for 30 GSS network (A.)

The analysis itself has then concentrated on the sensitivity of SISMA determination when removing one or more GSS.

From the analysis it shows that for the most of GSS stations, if one of them is failed due to whatever reason, there is no significant impact on SISMA performance found based on current SISMA algorithms [6],[7]. An exception is when a GSS station in Christmas Island or Kiribati is failed. Then there is a considerable SISMA performance degraded in the area near Christmas Island, i.e. the computed SISMA value is >0.70 m. However in the following an outage scenario in Europe/Africa has been developed for presentation in this paper to demonstrate the effects over more populated areas.

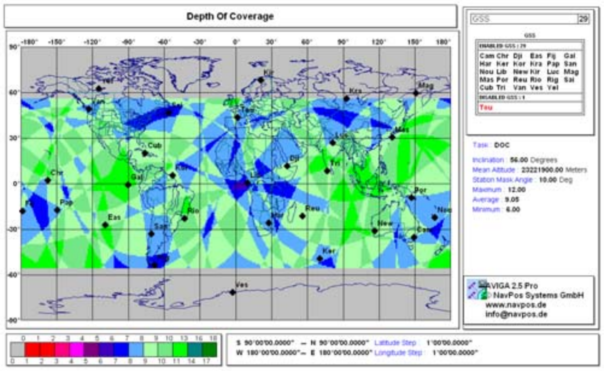

Figure 7: DOC coverage for a 30 GSS network with one Outage: Tou

This graph shows that through the outage of 1 GSS the DOC is regionally degraded, however is with 6 still above the required 4.

The resultant SISMA plot is shown in the next graph.

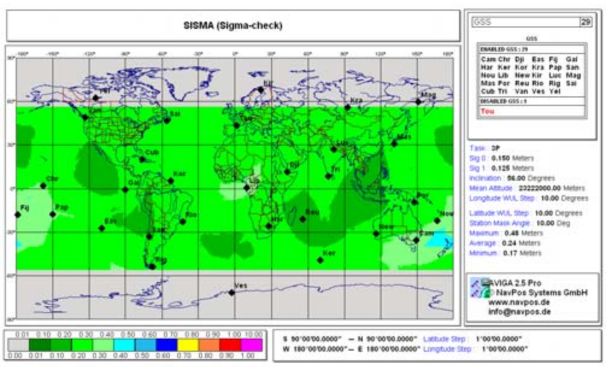

Figure 8: SISMA map for 30 GSS network (A.) with 1 Outage: Tou

Compared with Figure 6 the overall SISMA south of Toulouse is lightly worse than before, particularly around Libreville. However it is still far below the required 70 cm. This is characteristical for almost all Single GSS outages as analysis has shown. The results over all Single GSS outages are presented in the Figure 9, where it is shown that only a single outage of two GSS, Christmas Island (Chr) and Port Moresby Papua (Por) will regionally lead to SISMA slightly higher than 70 cm.

Such that it can be said that the 30 GSS network provides sufficiently margins against outages of one GSS.

To get a SISMA above 70 cm one has to consider further outages and in the following this has been performed for up to 4 GSS outages around Toulouse.

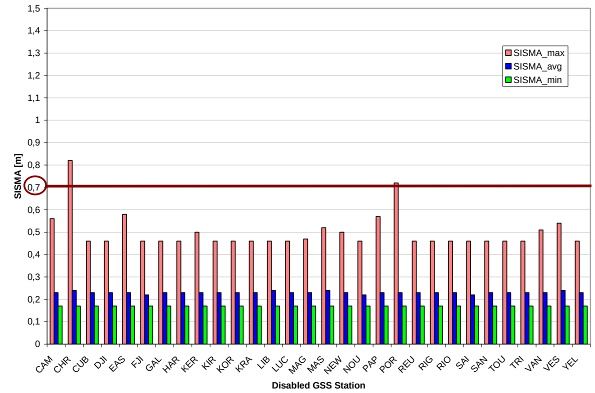

Figure 9: SISMA impact in Single Outage Scenarios; 30-GSS netw; GSS errors – model A.

In the following order the GSS stations have been removed from computation:

- Tou...Toulouse (Europe)
- Lib...Libreville (Africa)
- Dji...Djibouti (Africa)
- Kir...Kiruna (Europe)

Also for all 4 GSS outages the lowest DOC is never below 6, this is such no factor.

There is more effect on SISMA. The results for SISMA show the following figures.

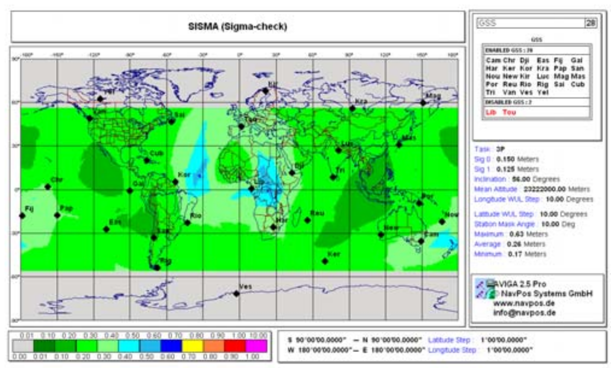

Figure 10: SISMA map for 30 GSS network (A.) with 2 Outages: Tou, Lib

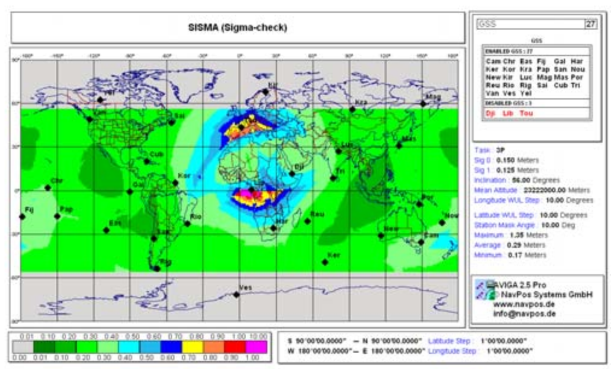

Figure 11: SISMA map for 30 GSS network (A.) with 3 Outages: Tou, Lib, Dji

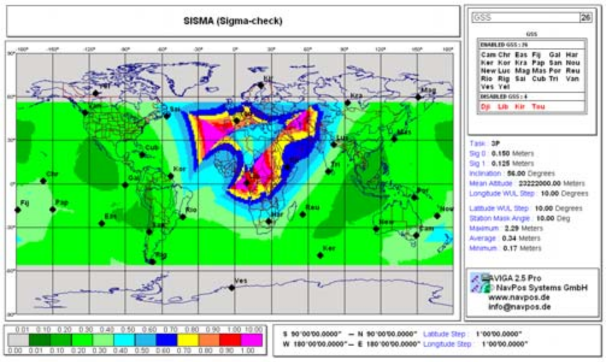

Figure 12: SISMA map for 30 GSS network (A.) with 4 Outages: Tou, Lib, Dji, Kir

The result is that even with 2 outages the worst SISMA will not degrade below the 70 cm requirement. This is changing only if excluding further GSS. Finally with 4 GSS out, there is a significant area with SISMA quite higher than the requirement with 2.2 meters as a maximum value in Figure 12.

As has been dicussed above the underlying assumption for GSS measurement quality seemed quite optimisticly to the authors such that an alternative budget has been anticipated assuming GSS clocks synchronisation errors and surveying errors. This resulted in a probably more realistic model **B.**

Applying this assumption to the SISMA computation the following results have been obtained relative to the above.

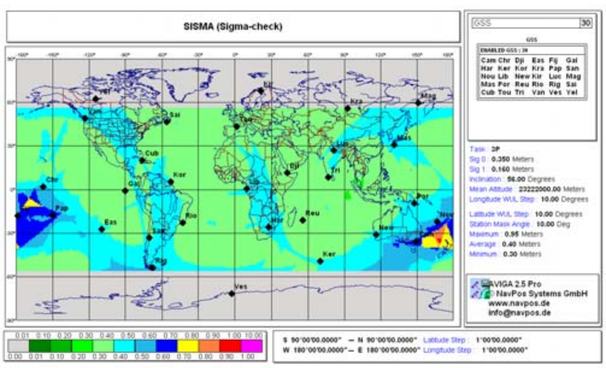

Figure 13: SISMA map for 30 GSS network (B.)

Figure 13 is the analogue to Figure 6. Already with the baseline GSS network there are areas where SISMA is above the requirements. This is an area around New Zealand (again) with maximum SISMA of 95 centimeters, and around Christmas Islands. The average SISMA is also much higher with 40 centimeters, however reasonably below the required 70 cm.

The single-outage computations were again repeated for all possible GSS outages with the result presented in the Figure 14. It can be seen that under assumption of a higher GSS measurement error budget according to model B.) any GSS outage causes regionally SISMA degradation greater than 70 cm, in worst case it is up to 1.45 meters. However in global average the SISMA are with 40 centimeters low enough. The question would be the effect on Integrity Risk computation for a user in the region.

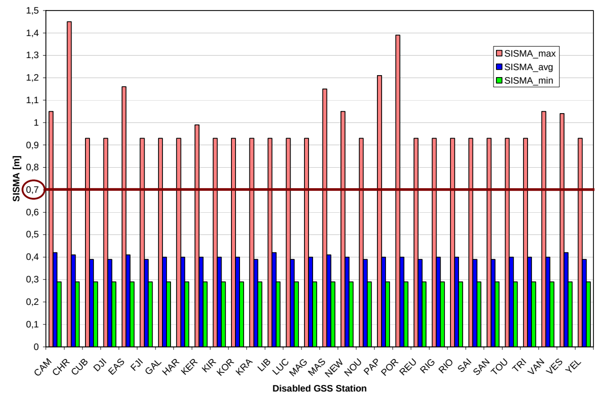

Figure 14: SISMA impact in Single Outage Scenarios; 30-GSS netw; GSS errors - model B.

For further outage analysis presented in this paper again the European/African GSS are removed.

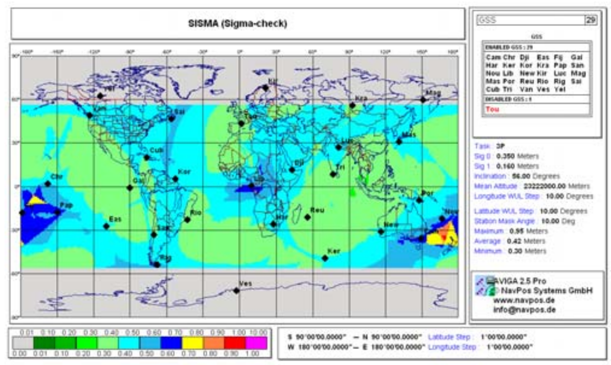

Figure 15: SISMA map for 30 GSS network (B.) with 1 Outage: Tou

One (Toulouse-) GSS outage is acceptable opening a degradation area around Libreville (close to 70 cm). This is typical that a failed GSS produces degradation far away. Further outages are more seriously, as the Figure 16 to Figure 18 show. With 4 Outages the worst SISMA is around 3.4 meters.

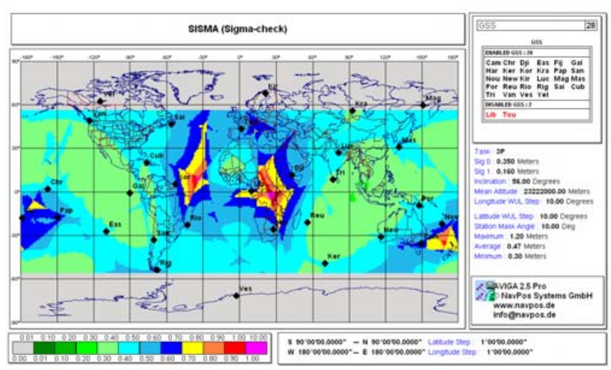

Figure 16: SISMA map for 30 GSS network (B.) with 2 Outages: Tou, Lib

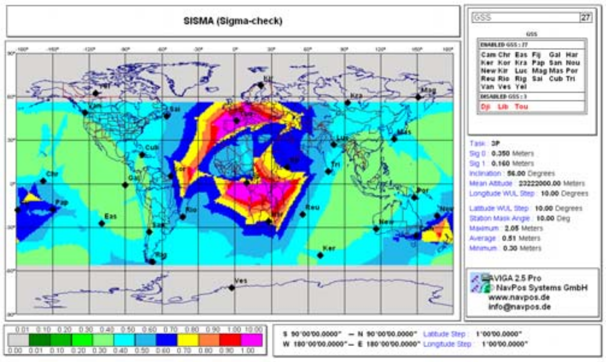

Figure 17: SISMA map for 30 GSS network (B.) with 3 Outages: Tou, Lib, Dji

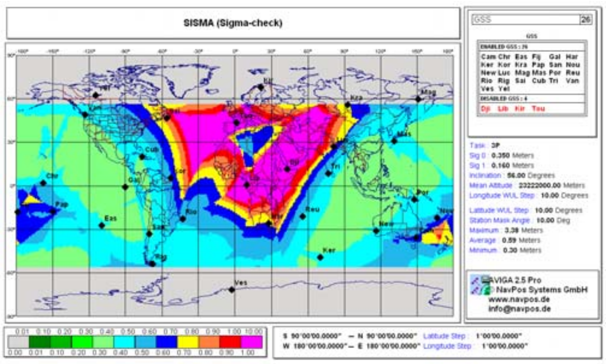

Figure 18: SISMA map for 30 GSS network (B.) with 4 Outages: Tou, Lib, Dji, Lib

If the assumption for GSS errors according to model B. is more realistic it seems that some additional GSS will be necessary to be deployed. This could bring back the robustness to SISMA computation. Such a 40 GSS network has been taken into account with stations taken from the proposal by GMS Requirements [3, Iss. 9], with the exception of Hawaii (Figure 4) as a first try.

The simulations wrt. to No-Outage and 4-Outage situation as the worst case is repeated then.

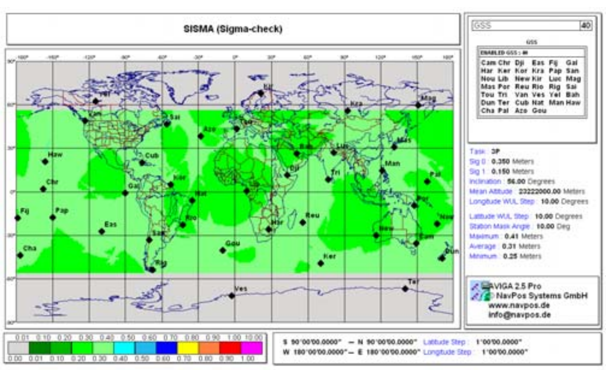

Figure 19: SISMA map for a 40 GSS network (B.)

For the single outage scenarios with the higher GSS error budgets (B.) a full set of simulations has been performed with the results consolidated in Figure 20.

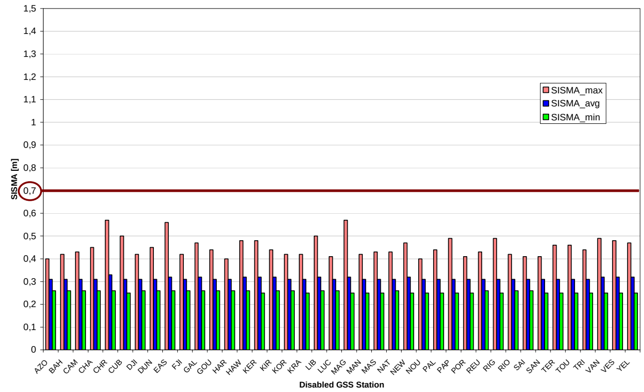

Figure 20: SISMA impact in Single Outage Scenarios; 40-GSS netw; GSS errors - model B.

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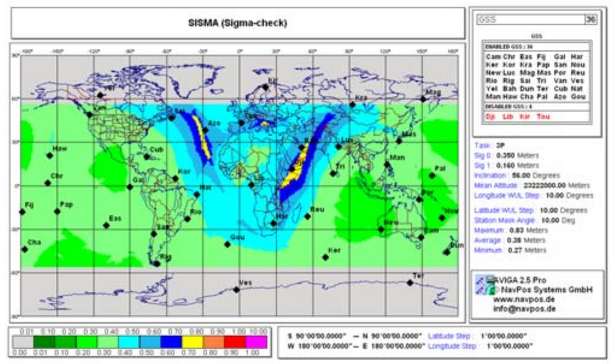

Figure 21: SISMA map for 40 GSS network (B.) with 4 Outages: Tou, Lib, Dji, Lib

It can be depicted of the above example (Figure 21 and Figure 19) that a 40 GSS network is much more robust particularly in a multi-outage scenario even if assuming the more grave GSS error model B. A one-outage scenario has no impact on SISMA degradation beyond the requirements of 70 cm (in nominal case) - Figure 20.

The next step has been to analyse the effects of the degraded SISMA performance on the User Algorithm level. Finally the user does not consider SISMA but Protection Level or in the new Galileo Integrity concept the Integrity Risk for a certain Alarm Limit (see Table 2). Before presenting simulation results, first the concept is outlined in the following.

GALILEO INTEGRITY RISK (USER CONCEPT)

According to approach [12], [13], the user receives direct information about the estimated performance of each satellite (SISA, SISMA, IF) . Processing this information per satellite in the navigation solution the user can evaluate the Integrity Risk (IR) and decide whether it is possible to start the operation or not. The overall or combined user integrity risk is defined from the equations published in [12]:

$$P_{HMI} = \overbrace{(1 - erf(\frac{VAL}{\sqrt{2}\cdot\sigma_{u,v}})}^{term\_1} + \overbrace{\sum_{io=1}^{n} p_{fail}\cdot\frac{1}{2}\cdot(1 - erf(\frac{VAL - \left|M_u[3,i_0]\cdot B_{0,i_0}\right|}{\sqrt{2}\cdot\sigma'_{u,v}(i_0)})}^{term\_2\_0}$$

$$+ \overbrace{\sum_{io=1}^{n} p_{fail}\cdot\frac{1}{2}\cdot(1 - erf(\frac{VAL + \left|M_u[3,i_0]\cdot B_{0,i_0}\right|}{\sqrt{2}\cdot\sigma'_{u,v}(i_0)})}^{term\_2\_1} +$$

$$+ \overbrace{\chi^2_{f=2}(\frac{HAL^2}{\xi^2})}^{term\_3} + \overbrace{\sum_{i_0=1}^{n} p_{fail}\cdot\chi^2_{nc,f=2}(\ (\frac{HAL^2}{(\xi'(i_0))^2}),(\frac{(M_u[1,i_0]\cdot B_{0,i_0})^2 + (M_u[2,i_0]\cdot B_{0,i_0})^2}{(\xi'(i_0))^2})\ )}^{term\_4}$$

(Eq. 6)

where [12]:

- VAL is the specified Vertical Alert Limit
- HAL is the specified Horizontal Alert Limit
- $\sigma_{u,v}$ is the standard deviation of the model CDF that overbounds the vertical position error in fault free state. defined in [12]
- $\chi^2_{f=2}(*)$ is the central chi-squared distribution with 2 degree of freedom (DOF), for DOF = 2 simple exponent
- ξ^2 is the variance of the model CDF that overbounds the fault free position uncertainty along the semi-major axis of the error ellipse in the xy plane
- n is the number of valid measurements
- i_0 denotes the index of a satellite with failed signal
- Pfail is the probability in any 150 s that one and only one of the received signals is outside the specification and flagged by the IF as “OK”
- $\sigma_{u,v}'$ (i_0) is the standard deviation of the model CDF that overbounds the vertical position error, when the satellite i_0 is failed
- B_0,i_0 is the (undetected) bias error affecting signal i_0
- $\chi^2_{nc,f=2}(*,p)$ is the non-central chi-squared distribution with DOF = 2 and parameter p
- $(\xi'(i_0))^2$ is the variance of the model CDF that overbounds the position uncertainty (for signal i_0) along the semi-major axis of the error ellipse in the xy plane when the signal i_0 is failed

SIMULATION RESULTS: INTEGRITY RISK

Based on the SISMA computations as performed above the following results are obtained for the maximum value of user Integrity Risk for the interesting Region with the outages (Europe & North Africa).

Figure 22 and the following are representing the Maximum Integrity Risk in a period of 24 hours for a User Grid mask of 1 degree and in time steps of 5 minutes. The presentation of the Integrity Risk is normalised using a logarithmic law to make the presentation better readible since integrity risks vary often in the order of 10^X !

$$P_{hmi}^{norm} = \log\left(\frac{P_{hmi}}{P_{hmi,0}}\right) \qquad \text{(Eq. 7)}$$

In the simulations the $P_{hmi,0}$ is set to $1.7x10^{-7}$ in 150 s = $1.133x10^{-9}$ in 1s, according to recommendations in [10].

Other parameters used for Integrity Risk have been derived from [10] and [6]:

- SISMA computation as above w. model **B.**
- OD&TS contribution: 65 cm
- SISA broadcast: 85 cm
- SISMA and TH simulated
- P_{md} for SISE of 5.9m: $5.8x10^{-3}$
- P_{fa} per sample: $1.5x10^{-5}$

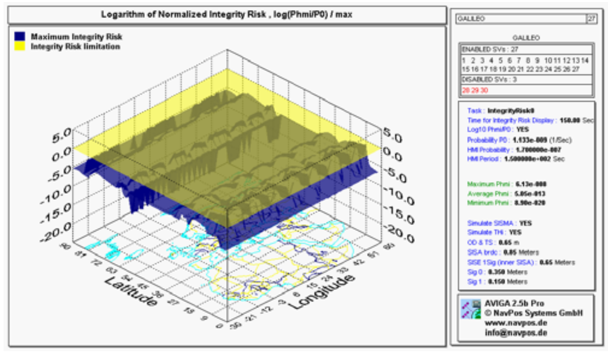

Figure 22: Maximum Galileo Integrity Risk (Model B., 30 GSS, 0 outages)

As expected with the nominal GSS stations and even assuming mod B. for SISMA computation a 100 % availability of Integrity Risk lower than the requirement is obtained. In comparison to the simulations in the previous papers [15] of the authors the (positive) difference is mostly based on

1. activation of SISMA simulation (instead a fixed 70 cm value)
2. reduction of SISA broadcast from 93 cm to 85 cm as the new baseline is.

Similar good results are also obtained with 1 (Tou) and 2 outages (Tou and Lib) where the Figure 16 let expect some problems due to appearing high SISMA at some regions. We need to take out 3 or 4 GSS to obtain a degraded Integrity Risk stepping over the required level. Figure 23.

These graphs present the worst case with the maximum Integrity Risk levels for each grid point reached in a sample period of 1 day. There are quite big regions where the IR has been above $1.7x10^{-7}$ with a maximum value of $2.76x10^{-6}$ which is a magnitude higher. However the duration of degradation could have been very short and is not represented by this type of graph.

To get a full statistic an Availability analysis has to be performed which is done with the used simulation tool via the PL/AL availability module. The PL are re-computed out of the Integrity Risk as described in the next chapter.

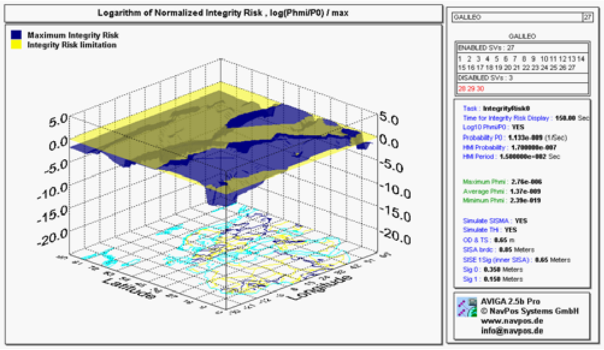

Figure 23: Maximum Galileo Integrity Risk (Model B., 30 GSS, 4 outages)

PROTECTION LEVEL & AVAILABILITY

The integrity risk PHMI calculated using Eq. 6 can be presented as the sum of the following terms :

term_1 is the probability of occurrence that the vertical position error will exceed VAL in the fault-free case when there is no bias pseudorange measurement on any of n satellite (this corresponds to SBAS).

(term_2_0 +term_2_1) is the probability that one of n satellite is failed i.e. has a bias B_{0,i_0} and the vertical position error associated with this bias is not detected by the IPF algorithms.

term_3 is the probability of occurrence that a horizontal position error will exceed HAL in the fault-free case when there is no bias pseudorange measurement on any of n satellite (this corresponds to SBAS).

term_4 is the probability that one of n satellites is failed i.e. has a bias B_{0,i_0} and the horizontal position error associated with this bias is not detected by the IPF algorithms.

Thus, P_{HMI} can be presented as sum of integrity risks in the horizontal and vertical planes

$$P_{HMI} = P_{HMI}^{Vert} + P_{HMI}^{Hor},$$

where

$$P_{HMI}^{VERT} = term\_1 + term\_2\_0 + term\_2\_1$$

$$P_{HMI}^{HOR} = term\_3 + term\_4 \qquad \text{(Eq. 8)}$$

Considering the left side terms in Eq. 8 as independent system parameters, it is still possible to treat the integrity equation Eq. 6 in a more traditional fashion. In this case the risks P_{HMI}^{VERT} and P_{HMI}^{HOR} are known and the user can solve Eq 6, 8 relative to HAL and VAL which can be thought of now as protection levels that is HPL and VPL. The results of the xPL availability computations based on this backward solution for Eq. 6 are presented below applying on the GSS scenarios discussed above.

SIMULATION RESULTS: AVAILABILITY

The following plots are based on the computation scheme above and present the VPL-II availability results averaged over a 1 day simulation period at time steps of 5 Minutes. The geographic grid spacing was 1° which represents 65340 user positions.

These availability plots can be referred to the above Integrity Risk and SISMA figures as follows:

VPL_av	SISMA	IR_max
Figure 24	Figure 13	Figure 22
Figure 25	Figure 16	-
Figure 26	Figure 17	-
Figure 27	Figure 18	Figure 23

Table 3: Simulation Result assignment

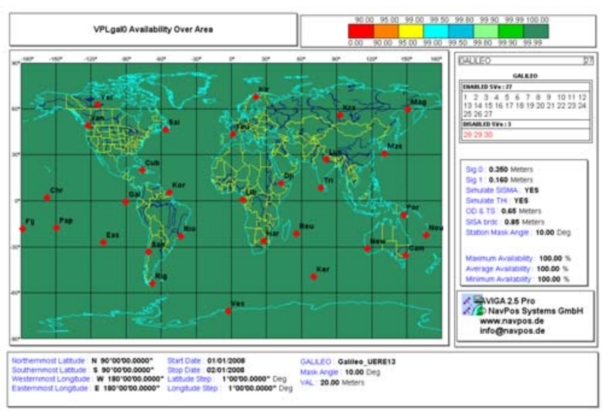

Figure 24: Galileo VPL Availability (APV-II) with GSS Model B.; 30 GSS; no outage

As Figure 13 and Figure 22 let expected the anticipated APV-II performance is met with this scenario fully world wide!

When considering a one-GSS outage also no degradation has been found. Just when taking into account a 2-, 3-, 4-outage scenario the availability will degrade below the levels required by the Galileo Mission requirements or ICAO requirements respectively. However this is valid mostly for dedicated regions. In world-average availability is sufficiently high (>99.8%) even in the case of Figure 27.

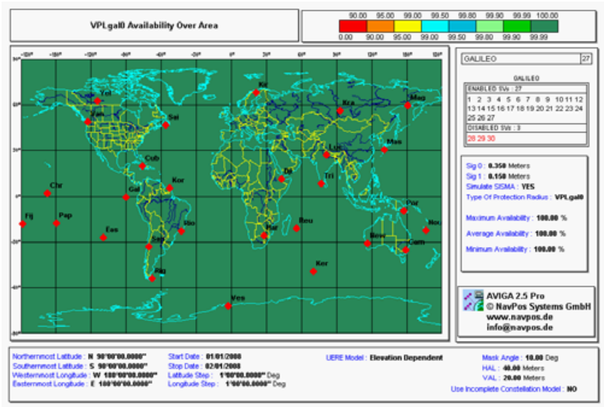

Figure 25: : Galileo VPL Availability (APV-II) with GSS Model B.; 30 GSS; 2 outages

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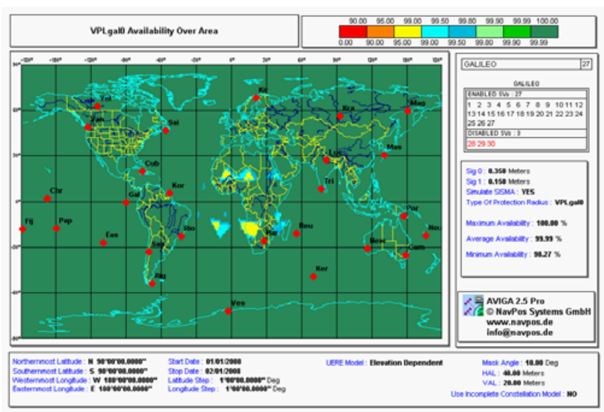

Figure 26: : Galileo VPL Availability (APV-II) with GSS Model B.; 30 GSS; 3 outages

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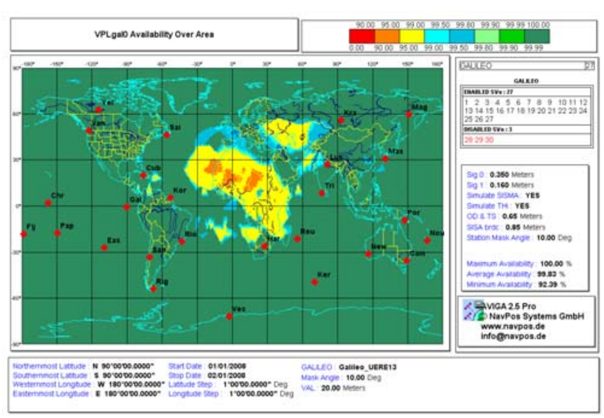

Figure 27: Galileo VPL Availability (APV-II) with GSS Model B.; 30 GSS; 4 outages

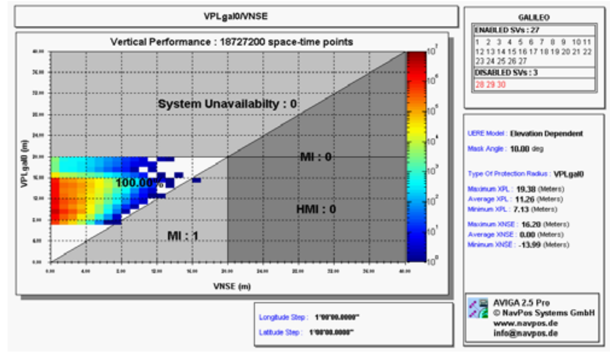

Figure 28: VNSE/VPL Availability over 1°x1° grid in 5 minute steps over 1 day

The AVIGA tool also offers to use the presentation form of the Stanford Graph for over area simulations. Usually the Stanford Plot is used to show the xNSE/xPL Availability at a given location i.e. one single position. In Figure 28 the presentation form of the Stanford Plot was used to show the simulation results for a worldwide 1°x1° grid (65340 positions) with 300s time steps over a 1 day Galileo repetition cycle i.e. 289 epochs. This amounts to already more than 18,6 Million space-time points which were simulated in one run. The result is a vertical availability of 100 %. This is valid for the 30 GSS scenario and SISMA modelled according GSS errors model **B.** The single Missed Indication event, which need not to be classified hazardously is generated by the random process for xNSE modelling and is on event out of 18 million, such representing the P_{md} .

The presented results are strongly dependent on the validity of the UERE definition for the user on one hand, the assumed SISA performance and last not least the GSS UERE' budged described with ***model A.*** and ***model B.*** in this paper however representing a UERE without the SIS (satellite orbit & clock residual errors) contributors.

The Galileo Integrity Concept is currently under consolidation. Above simulations are based on the specification basically as given in [6] and [10]. Further conceptual refinements are being developed and are currently in the process of getting implemented.

CONCLUSIONS

The Integrity determination and provision function within Galileo is one of the major challenges in the System development. The layout (number and distribution) of the Galileo Sensor Station network and also the underlying Integrity Concept is crucial for fulfilling the demanding requirements for Safety Of Life applications, particularly these of aviation APV-II precision approaches.

This paper has examined the sensitivity of the performance to the GSS outages. It has been shown that with the baseline GSS network of 30 stations a robust Integrity System can be provided, which is quite insensitive to one-GSS outage. This is given however assuming a quite optimistic ranging error budget for GSS stations.

In that case the specified SISMA determination performance can be globally met with few exceptions. APV-II requirements for VPL availability are met easily in a one-outage scenario. Only in multiple GSS outage scenarios the Availability performance will be degraded in some regions.

If however assuming higher GSS error budgets the sensitivity for one-GSS outages is much more evident, particularly in multiple outage scenarios. Then the effects on SISMA performance and Integrity Availability performance are not neglectable any more on a wider regional level.

This problem seems to be solvable if adding additional GSS to the Ground Segment. A 40 GSS constellation indicates in the analysis performed so far, that the sensitivity even to 2-GSS outages is then quite low. However the analysis has not yet regarded at all dual GSS failure combinations.

Finally, it is to be mentioned that this analysis is based on the assumption that the Galileo UERE specification for Safety of Life applications is achieved and also the GSS error budget is achieved as assumed. Also no implication of GSS outages on SISA broadcast is considered.

With the launch of the first Galileo satellites (GSTB-V2) the UERE budget can be validated in both cases, User and GSS. The analysis will have to be repeated once the budgets are confirmed/reassessed.

To analyse the situation in depth also additional extended and systematic simulations should be performed using different error budget assumptions, different GSS distributions and involving Space and Ground segment outage schemes. Also the latest SISMA computation algorithms and assumptions should be implemented in the Service Volume Simulation tool.

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